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NASA TECHNICAL TRANSLATION

NASA TT F-14,715

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Translation of: "O vozmozhnostyakh termicheskogo zondirovaniya atmosfery Marsa," Kosmicheskiye issledovaniya, No. 1, 1972, pp. 92-99 v.10

(NASA-TT-F-14715) THE POSSIBILITIES OF THERMAL SOUNDING OF THE ATMOSPHERE OF MARS Y.M. Timofeyev, et al (NASA) Nov. 1972 14 p CSCL 03B

N73-11859

Unclas

G3/30 46625

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 NOVEMBER 1972

THE POSSIBILITIES OF THERMAL SOUNDING OF THE ATMOSPHERE OF MARS

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ABSTRACT. The possibilites of obtaining temperature profiles of the atmosphere of Mars by interpreting the spectral relationship of the outgoing thermal radiation from the planet are reviewed. The mean error in the temperature reconstruction for all temperature profiles investigated is approximately 9°K for measurement errors of 1-2%. All features of temperature profiles, ground and altitude temperature inversions, can be detected.

A wide-ranging scientific program of research on the planets in the solar system (Venus, Mars, and others) has been conducted in recent years [1-3]. And the most diverse methods have been used; direct and indirect, ground, and with the aid of artificial space vehicles. It can be anticipated that in the near future even greater attention will be given to the study of the composition, temperature, and circulation of the planet's air masses. Indirect methods, based on interpreting the measurements of different characteristics of the field of the outgoing radiation from planets, can be singled out as the methods providing the best prospects for obtaining large amounts of information on the parameters of the physical state of the atmosphere. The advantages of these methods can be used with particular rationality if the corresponding radiation characteristic measurements are made from artificial planetary satellites (APS). /92*

Indirect methods of sounding the atmosphere, as well as the underlying surfaces, are widely used today to obtain information on the global state of the earth's atmosphere [4-6]. Right now, for example, measurement by AES [artificial earth satellites] enable us to construct global charts of temperatures of the underlying surfaces, charts of cloudiness, of vertical temperature profiles, of humidity, and ozone.

This paper will review the possibilities of obtaining temperature profiles of the atmosphere of Mars by interpreting the spectral relationship of the outgoing thermal radiation (the thermal sounding method [6]). It is known that thermal radiation is a complex functional of vertical temperature profiles

* Numbers in the margin indicate pagination in the foreign text.

absorbing components of the atmosphere that depends on the radiation capacity of the underlying surface, on the properties of the spectral interval considered, and the like. If we know a number of the distributions and parameters, such as the distribution of the absorbing material, and the characteristics of absorption, for example, the magnitudes of the thermal radiation can be determined by the vertical temperature profiles, and can serve as the source of information about the profile, T. The physical basis of the possibility of obtaining just such a temperature profile is the fact that the outgoing radiation can be generated by different layers of the atmosphere in the different spectral intervals. This makes it possible to evaluate the qualitative type of vertical profile, T, and the mean temperatures of the different layers of the atmosphere, even without using the complex procedures of interpreting measurments. This is precisely the approach that made it possible for the authors of reference [7] to arrive /93 at an important conclusion concerning the presence of a positive T gradient in the upper layers of the atmosphere of Venus above the clouds.

The difficulties in solving the problem of thermal sounding the atmosphere of Mars are occasioned by an insufficient amount, and poor quality, of the a priori information on the parameters of the physical state of the atmosphere needed to correctly solve the inverse problem, as well as of the properties of the reaction between the radiation and the medium for conditions observed in the atmosphere of this planet (low pressures and temperatures, large masses of absorbing gas, CO_2). However, numerical experiments to reconstruct the T profile for ground conditions have shown [6] that even when quite large errors are made in assigning the properties of absorption and condition of the atmosphere it has been possible to reconstruct the temperature with a 5 to 10° error, and this is quite acceptable in the first stage of investigating planets.

There is the possibility of setting up complex experiments by indirect sounding of the atmosphere using APS in which the measurements of the radiation are not just limited to eigenmeasurements of the planet. For example, we can, by measuring the scattered and reflected radiation from the sun, or from other artificial sources of light in the CO_2 absorption bands located in the near infrared region of the spectrum, in principle, determine independently the profile of the absorbing gas, pressure at the surface of the planet, and other features [5, 6]. Thus, the method presented in this paper can be considered part of a complex experiment designed to study the atmosphere of Mars.

Results of Calculations of Outgoing Radiation

References [8, 9] contain the calculations for outgoing radiation in a broad band of wavelengths. The calculations in [8] were made for quite a coarse spectral resolution. As experience in solving the problem of thermal sounding of the earth's atmosphere has shown, it is desirable to solve the inverse problem by using measurements with quite good spectral resolution. The integral form of the equation for the transfer of radiation is used to solve the direct, as well as the inverse, problem in the infrared. The following expression can be written for outgoing thermal radiation at the upper boundary of the atmosphere in the vertical direction

$$I_{\Delta\nu} = \int_0^{p_0} B_{\bar{\nu}}[T(p)] \frac{\partial P_{\Delta\nu}[p, q(p), T(p)]}{\partial \lg p} d \lg p + B_{\bar{\nu}}[T(p_0)] P[p_0, q(p_0), T(p_0)], \quad (1)$$

where

$I_{\Delta v}$ is the intensity of the outgoing radiation in the spectral interval Δv;

P_0 is the pressure at the surface of the planet;

$T(p)$ is the vertical temperature profile;

$B_{\bar{v}}$ is a function of Planck radiation from an absolutely black body for the mean frequency of the interval Δv;

$P_{\Delta v}$ is a function of the passing from the upper boundary of the atmosphere to a level with pressure p depending, in the general case, on $T(p)$;

$q(p)$ is the vertical distribution of the absorbing component.

Eq. (1) can be obtained with a whole series of simplifying assumptions: (a) scattering of infrared radiation in the band of the spectrum considered (the CO_2 bands when $\lambda \approx 4.3$ and 15 microns) can be ignored; (b) the condition of local thermodynamic equilibrium (LTE) is satisfied in the atmosphere of Mars; (c) the surface of the planet has a radiation capacity $\delta = 1$.

In the case of the low pressures found in the atmosphere of Mars, it can be expected that beginning at some altitude the assumption of LTE will not be valid, and this is associated with the low frequency of collisions of molecules and the limited lifetimes of the excited states of the molecules. There are various /94 estimates, for example, that given the condition in the earth's atmosphere, one will observe an upset in the LTE at pressures less than 0.8-0.05 mb (for different intervals in the CO_2 bands). Since we do not have corresponding data for the Martian atmosphere we assume that we can ignore possible deviations from the LTE in the first stage.

The following assumptions concerning the model of the atmosphere were used for the calculations: the pressure at the surface of the planet was 10 mb; the dominant gas was CO_2 (two cases were considered, 100 and 80% CO_2 content); the temperature profiles were borrowed from a theoretical paper [10]. Figure 1 shows the T profiles for which the calculations were made. While the presence of other gases has been detected in the Martian atmosphere [11], their influence on the outgoing radiation in the vertical direction is slight, because their content is so low.

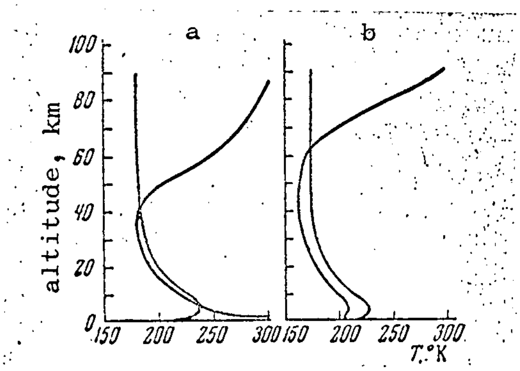

Figure 1. Temperature-altitude profile for a Martian atmosphere with a 100% CO_2 content below the far side in latitude -8° (a) and above the near side in latitude +8° (b).

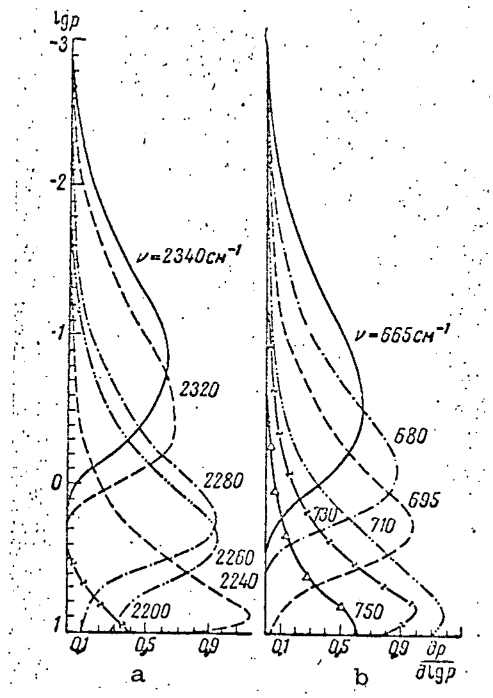

Figure 2. The weighting functions $\partial P_{\Delta\nu}/\partial \log p$. a - for the CO_2 4.3 micron band; b - for the CO_2 15 micron band.

The data contained in reference [12] and the effective mass method were used to calculate the passing functions for an inhomogeneous atmosphere. (Passing functions for P_0 = 10 mb when T = 200 and 250°K were used). We note that we do not now have the necessary volume of information on the passing of infrared radiation by CO_2 gas for large values of absorbing masses, low temperature and pressures. A quasistatistical model of the Lorentz absorption line contours were used to obtain the passing functions in reference [12]. Naturally, a definite influence of the Doppler effect on the magnitude of the passing can be expected when $p < 10$ mb. Special evaluations [9], made using the data contained in reference [13], revealed that the error in passing attributable to the failure to include the influence of the Doppler effect can be observed only in the wings of the absorption bands we have considered (up to 40-50%). In all other cases (for the 15 micron bands in the broad band of the spectrum from 600 to 730 cm^{-1}, for example) the errors are slight. This can be explained by the fact that under Martian atmospheric conditions the spectral intervals considered are in the region of heavy absorption [14], the result of the great number of absorbing substances.

So-called weighting functions, $\partial P_{\Delta v}/\partial \log p$, were devised to analyze the physical picture of the formation of the outgoing radiation, as well as to arrive at a qualitative determination of the possible boundaries of vertical sounding of the atmosphere. Figure 2 shows the weighting functions for different spectral intervals in the CO_2 bands for 4.3 and 15 microns. As we see from the figure radiation in the centers of the bands (665 and 2340 cm^{-1}) is generated by rarefied layers of the atmosphere remote from the surface of the planet. In the spectral intervals near the wings of the bands the generation is by those adjoining the surface layers (750 and 2240 cm^{-1}). Evaluating the possible upper boundaries of sounding from the form of weighting functions, we obtain $z_m \approx 60$ km (p = 0.025 mb) for the 4.3 micron band, and $z_n \approx 50$ km (p = 0.08 mb) for the 15 micron band. We note that the caluclation for the weighting functions shown in Figure 2 was made for spectral resolution at 5 cm^{-1}. Corresponding calculations for resolution at 15 cm^{-1} have shown that in the case of lesser spectral resolution there are marked changes in the weighting functions only near the centers of the bands, and that, specifically, the sounding ceiling drops to an altitude of $h \approx 47$ km in the case of the 15 microns for the CO_2 band. /95

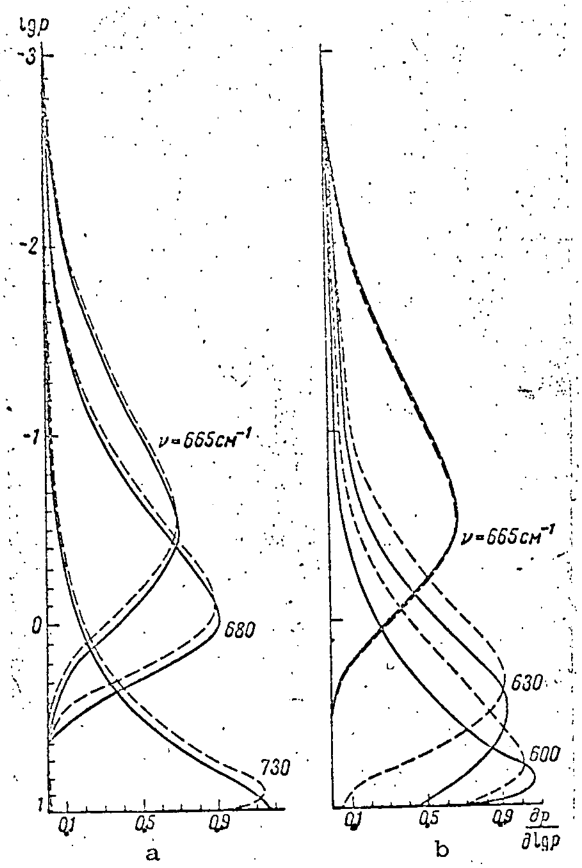

Figure 3. Change in weighting functions $\partial P_{\Delta v}/\partial \log p$ attributable to variations in (a) the CO_2 gas content, the dashed line for 100% CO_2 content, the solid line for 80% CO_2 content; and (b) the temperature, the solid line when T = 200°K, the dashed line when T = 250°K.

Figure 3 shows the results of calculations enabling us to evaluate the variations in the weighting functions attributable to variations in the content of CO_2 gas and in the temperature (the case of the 15 micron band). Change in the CO_2 content from 100% to 80% causes definite changes to occur in the weighting functions. And there is a displacement of the weighting functions to the region high pressures, with the differences in $\partial P_{\Delta v}/\partial \log p$ in the tens of percent. The influence of temperature (Figure 3b) shows up only for the intervals in the wings of the bands, and this is associated with the definite temperature dependency of the passing function (we should point out that the weighting functions in this figure were calculated for a 100% CO_2 content, and for two mean effective atmospheric temperatures, 200 and 250°K). Note that there is a displacement of the weighting functions into the region of lower pressures with increase in the temperature.

Calculations for a fine structure of the spectrum of outgoing radiation with resolution at 5 cm^{-1} were made (Figure 4) for the temperature profiles (Figure 1). As will be seen from the figure, the maximum values for the radiation will be found for the wings of the bands for both absorption bands, and this can be attributed to the formation of the radiation for these spectral intervals in the lower, warmer, layers of the Martian atmosphere. An interesting feature of the spectra is the presence of radiation maxima in the centers of the bands for temperature profiles T_2 and T_4. This is associated with the fact that temperature /96 inverstions at high altitudes is characteristic of them, and also is responsible for the radiation in these spectral intervals. This is manifested in particular in the 4.3 micron band, the result of the strong temperature dependence of the radiation from an absolutely black body for the range of the spectrum considered and for the temperatures found in the Martian atmosphere. This further serves to explain the significantly larger relative variations in the outgoing radiation in terms of T variations for the 4.3 micron band, compared to the 15 micron band.

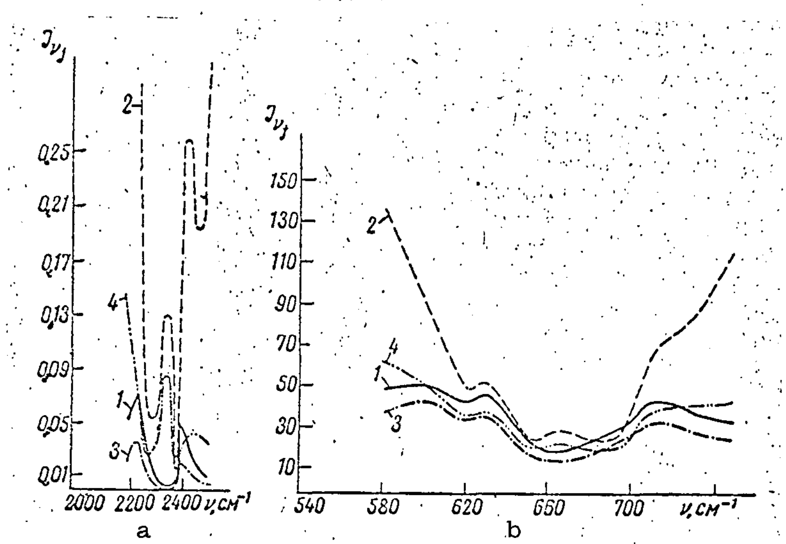

Figure 4. Spectral dependence of outgoing radiation at the nadir for the CO_2 15 micron (a) and 4.3 micron (b) bands. 1 - T_1, 2 - T_2, 3 - T_3, 4 - T_4.

We note that the local maximum in the centers of the bands, indicating the presence of an altitude inversion in the Martian atmosphere, is found only when spectral resolution is high. It will be practically indistinguishable when $\Delta v = 15\ cm^{-1}$ for the 15 micron band, for example. This peculiarity is the result of the displacement of the weighting functions to a lower layer when the spectral resolution is reduced, something we mentioned earlier. So we can conclude that measurements with high spectral resolution are required in order to observe these altitude features of the temperature profile of the Martian atmosphere.

The CO_2 band at 4.3 microns could be recommended to solve the inverse problem, at least from the point of view of the changeability of the outgoing radiation in terms of T variations. But because of the low temperatures observed in the Martian atmosphere, the magnitudes of the outgoing radiation in this region of the spectrum are very small, 0.01-0.25 erg/cm^2-sec-sr-cm^{-1}. At the same time, for the 15 micron band it is 20-100 erg/cm^2-sec-sr-cm^{-1}, and at least we can, at this time and for this band, make measurements with a sufficiently high relative accuracy (1-5%). Hence, we conducted numerical experiments concerned with the solution of the inverse problem only for the case of measurements in the 15 micron band.

Solution of the Thermal Sounding Problem

When information on the pressure at the surface of the planet, on the surface temperature, T_0, are available, and when knowledge of the distributuion of CO_2 gas, as well as the negligibly weak temperature dependence of the passing function, is available, the task of reconstructing the vertical profile of the temperature in terms of the outgoing radiation spectrum reduces to solving the classically uncorrected Fredholm integral equations of the first kind /97

$$f(\nu)=\int_0^{p_0} k(\nu,x)\varphi(x)\,dx, \tag{2}$$

where

k(v, x) is the kernel of the integral equation, which is taken as given.

The numerical solution of Eq. (2) can be approximated by a system of algebraic equations which can be written in the matrix form

$$f=K\varphi, \tag{3}$$

where

K is a matrix describing the conversion of the vector of the values of the unknown characteristic φ into a vector of the values of the measured function f.

A stable solution of Eq. (3) can be arrived at by using the regularization method proposed by one of the authors of this paper in [15]. In this approach the unknown vector, φ, is sought for in the form of an expansion

$$\varphi = \sum_{i=1}^{m} C_i \varphi_i \tag{4}$$

in terms of a system of vectors, φ_i, orthonormalized in the sense of a scalar product

$$(H\varphi_i, \varphi_j) = \delta_{ij} \qquad (i, j = 1, \ldots, m).$$

The concrete form of a symmetricaly, positively defined, matrix H will depend on the nature of the a priori assumptions made as to the unknown function. With no detailed information on the temperature distributions in the Martian atmosphere available to us, we used the assumption of smoothness of the solution. In this case the matrix H can be selected on the basis of a finitely different approximation of the integral of the "smoothness" of the solution of the following type

$$(H\varphi, \varphi) \approx \int [\varphi'(x)]^2\, dx.$$

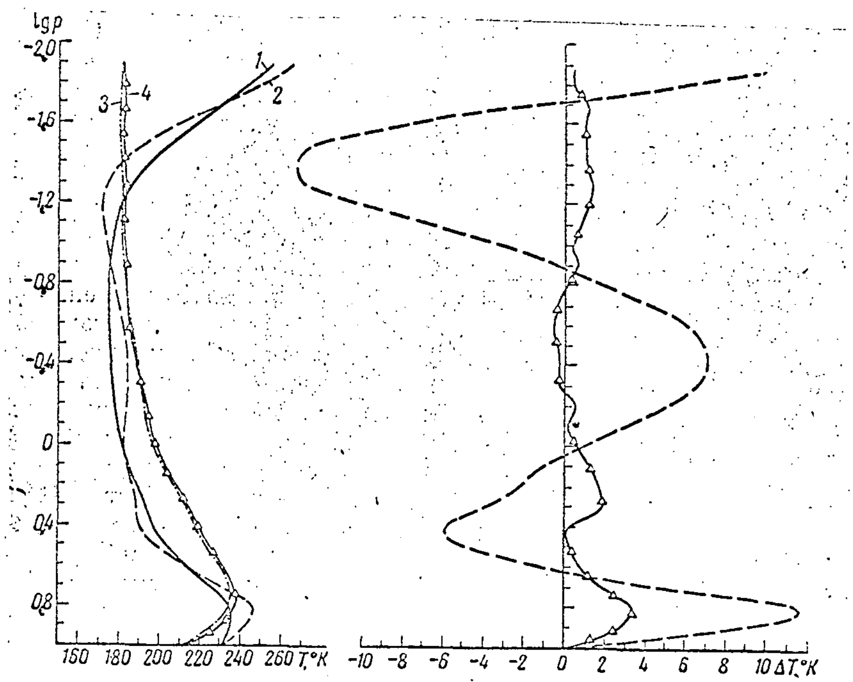

Figure 5. Reconstruction of temperature profiles at the 2% error level. 1 - accurate T_4 profile; 2 - reconstructed T_4 profile; 3 - accurate T_1 profile; 4 - reconstructed T_1 profile.

A limited number of terms in the series were considered in order to stabilize the solution of Eq. (2), stable during the numerical transformation into the expansion of Eq. (4), and their number was selected for the condition [15] /98

$$f_i > 1.5\sigma, \qquad (5)$$

where

f_i is the projection of the function f on the ith eigenvector, l_i, $f_i = (f, l_i)$;

σ is the dispersion in the random error made in the measurments, including the known.

The numerical experiments conducted in accordance with the closed scheme for three levels of random error (0.1 and 2%) revealed that the Eq. (5) criterion denoted an optimum number of terms in the Eq. (4) expansion in the majority of cases. When the criterion indicated an untrue number of terms in the expansion the loss in accuracy in restoring the T profile was slight.

The solution of the inverse problem was derived for the profiles shown in Figure 1. Used as the "measured" were 6 or 10 values of the outgoing radiation for different spectral intervals within the 15 micron CO_2 band. Selection of these intervals was made on the basis of an analysis of the weighting functions, and of their disposition in the atmosphere. In the case of the 6 measurements, the central frequencies of the spectral measurments were: 585; 627.5; 640; 645; 662.5; 667.5; and in the case of the 10 were 585; 625.0; 627.5; 632.5; 640; 645; 660; 662.5; 665.0; 667.5 cm^{-1} (the spectral resolution of the measurments was 5 cm^{-1}). The numerical experiments revealed that the accuracy of the reconstruction changed but little with increase in the number of measurments from 6 to 10 values of outgoing radiation when errors were 1 and 2%. This tells us that at these levels of experimental error, the number of independent parameters contained in the radiation measurements is small and less than 6. This was confirmed during an informative, approximate, analysis that showed that when measurement errors were 1-2%, the measurements contained information from 3 to 5 independent parameters as to the temperature profile (depending on the type of profile, and measurement errors). Figure 5 is an example of the reconstruction of profiles at the 2% error level. As we see, the thermal sounding method enables us to obtain good reconstruction even of the quite complex behavior of the temperature in the Martian atmosphere. The mean error in the temperature reconstruction when the measurement errors were 1-2% was 5-9°K for all the temperature profiles we studied. It is important to emphasize the fact that although the maximum errors in the reconstruction were ~ 10°K, we still were able to detect all the peculiarities of the temperature profiles; the ground and altitude temperature inversions.

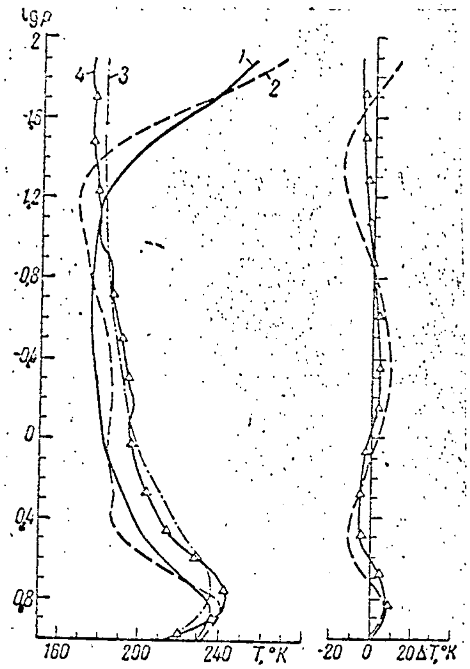

Figure 6. Reconstruction of temperature profiles at the 2% error level and for errors in kernel assignment. 1 - accurate T_4 profile; 2 - reconstructed T_4 profile; 3 - accurate T_1 profile; 4 - reconstructed T_1 profile.

Considering that, in real reconstruction, the inversion of the problem will come about when there is an error in the kernel of the integral equation, Eq. (2) ($\partial P_{\Delta v}/\partial \log p$), because of the most diverse of reasons, we also modeled this reconstruction case. At the same time, the direct problem was solved with a kernel corresponding to a 100% CO_2 content, the inverse with an 80% content. Now the disturbance in the kernel (Figure 3) is quite considerable. Accuracy of reconstruction deteriorates significantly when two types of errors, measurement and the assignment of the kernel of the equation, are present. The fact that the Eq. (5) criterion now functions much /99
less effectively plays a significant part here. Figure 6 shows examples of the reconstruction of profiles T_1 and T_4 for 2% measurement errors, and for errors in kernel assignment. Here the reconstruction errors are ~ 15°. The distortions in the regions of complex behavior of the T_4 temperature profile are particularly great. But even here it was possible to reconstruct the basic qualitative behavior patterns in the temperature distribution. All of the results of these experiments show that we need a complex approach to the investigation of the atmosphere, particularly independent determinations of the profile of CO_2 gas in the atomsphere in order to have a sufficiently accurate

reconstruction of temperature in the Martian atmosphere.

Upon analyzing all of the results, we can conclude that the thermal sounding method is a future method for studying the thermal structure of the Martian atmosphere, one that will enable us to obtain new information about the T profile, even when there are large errors in measurements in the given physical state of the atmosphere.

Submitted 17 May 1971

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